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Review Article

Carbon Literacy in Higher Education: A Systematic Review of CO_2 Emission Education and Its Impact on Student Behavioral Change

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Abstract

Carbon literacy education has emerged as a key strategy for addressing climate change by enhancing environmental awareness and promoting pro-environmental behavior among university students. This study presents a systematic literature review examining how CO_2 emission education is conceptualized, implemented, and evaluated within higher education institutions and its influence on student behavioral change. This review synthesizes peer-reviewed studies published between 2015 and 2026, focusing on conceptual frameworks, pedagogical approaches, and behavioral outcomes. The findings indicate that carbon literacy education improves climate knowledge, strengthens environmental attitudes, and increases students' intentions to adopt sustainable practices in the future. Pedagogical strategies, such as experiential learning, project-based learning, life cycle assessment, and campus-based sustainability initiatives, play a critical role in translating knowledge into actionable competencies. However, a persistent awareness–action gap remains, wherein increased knowledge does not consistently lead to sustained behavioral change. The effectiveness of educational interventions is strongly influenced by psychological engagement, social learning environments and institutional support. Overall, this study emphasizes the need for integrated and interdisciplinary approaches that combine cognitive, experiential, and institutional dimensions. Embedding carbon literacy across curricula and campus practices can enable higher-education institutions to foster meaningful behavioral change and contribute to climate-mitigation efforts.

Keywords: Carbon literacy, climate change education, CO_2 emission education, higher education, pro-environmental behavior

1. Introduction

Climate change has emerged as one of the most pressing global challenges of the twenty-first century, primarily driven by the continuous increase in greenhouse gas emissions, particularly carbon dioxide (CO_2), resulting from human activities such as energy consumption, transportation, mining, and industrial production (Anwar et al., 2024; Hardyanti et al., 2022; Wibowo et al., 2025). The growing concentration of atmospheric CO_2 has intensified global warming, extreme weather events, and ecological disruption, thereby raising urgent concerns regarding sustainable development and long-term environmental resilience (Hardyanti et al., 2022). In this context, education has been widely recognized as a critical mechanism for fostering environmental awareness and equipping individuals with the competencies required to mitigate climate impacts. Higher education institutions (HEIs) play a strategic role in cultivating carbon literacy among university students, which is defined as an understanding of carbon emissions, their sources, and the actions necessary to reduce them in personal and societal contexts. Universities function not only as centers of knowledge production but also as transformative environments that shape students' environmental values, decision-making processes, and sustainability-related behavioral practices. Through integrated teaching, research, and community engagement activities, HEIs influence how students interpret climate challenges and develop the capacity to adopt low-carbon lifestyles. Therefore, developing carbon literacy among students is essential because it connects the scientific knowledge of climate change with everyday behavioral choices, enabling individuals to translate environmental understanding into practical actions that contribute to emission reduction and long-term environmental stewardship.

Existing scholarship has increasingly explored the role of higher education in advancing climate change education and promoting student sustainable behavior. Empirical evidence suggests that increased awareness of carbon emissions is associated with measurable differences in lifestyle choices and environmental practices. For instance, machine learning analyses of student lifestyle emissions demonstrate that individuals with stronger carbon awareness are significantly more likely to exhibit lower-emission behavioral patterns than those with limited awareness (Cen et al., 2025). Similarly, integrating sustainability concepts into university curricula, particularly through incorporating Sustainable Development Goal 13 on climate action, has been shown to strengthen students' understanding of climate challenges and enhance their engagement with mitigation strategies (Tarrazó-Serrano et al., 2024). Universities also function as living laboratories, where students' everyday practices, including energy consumption, transportation, and food choices, can be examined and reshaped through institutional sustainability initiatives. Modeling studies indicate that coordinated campus interventions combined with community engagement can significantly reduce student-related carbon emissions, with scenario simulations suggesting potential reductions of up to 40 percent when campus policies align with community actions (Zhu et al., 2026). In addition, educational programs, such as workshops, internships, and community-based sustainability projects, allow students to apply theoretical knowledge in real-world contexts while developing leadership competencies relevant to climate mitigation (Atef and Ramachandran, 2026). Complementing these initiatives, curricular innovations addressing low-carbon technologies and environmental policy further equip students with technical knowledge and professional skills necessary for addressing sustainability challenges (Yu et al., 2013)

Despite these promising developments, the existing literature reveals several conceptual and empirical limitations that constrain our understanding of how carbon literacy education influences student behavior in higher education contexts. One persistent issue is the widely documented awareness–action gap, where students demonstrate high levels of environmental knowledge but fail to consistently translate this knowledge into sustainable behaviors. Studies examining students' perceptions of climate change indicate that although many students acknowledge the environmental and societal importance of sustainability, their actual engagement in climate-friendly practices remains limited (Lingos et al., 2025). This gap suggests that cognitive awareness alone may be insufficient to generate meaningful behavioral transformation, emphasizing the importance of psychosocial factors such as environmental

values, risk perception, and emotional engagement in shaping pro-environmental behavior (Garrecht et al., 2026). Moreover, institutional challenges influence the effectiveness of sustainability education. Many universities publicly commit to climate action but struggle to translate institutional awareness into consistent operational practices and student engagement strategies (Kumbhojkar and Raman, 2024). Methodological inconsistencies further complicate the evaluation of sustainability initiatives, as variations in carbon footprint assessment methods and system boundaries hinder comparisons across institutions and limit the identification of best practices (Da Silva et al., 2023; Valls-Val and Bovea 2021). These limitations indicate the need for a comprehensive synthesis of existing research to better understand how carbon literacy education is conceptualized, implemented, and evaluated in higher education settings.

Recent review studies have begun to examine the role of higher education in advancing sustainability and climate-related competencies; however, their scope remains fragmented across conceptual and methodological domains. For example, reviews of decarbonization and green campus strategies primarily focus on institutional emissions and operational practices, with limited attention to student behavioral outcomes (Da Silva et al., 2023; Oliveira and Proença, 2025). Similarly, literature reviews on carbon footprint assessment in higher education emphasize methodological frameworks and measurement approaches but do not explicitly address the pedagogical mechanisms that influence student behavior (Valls-Val and Bovea, 2021). Other reviews on sustainability education highlight the importance of interdisciplinary learning and competency development, yet often treat climate literacy and carbon-related behavior as secondary outcomes rather than central analytical focuses (Price et al., 2024). Consequently, existing reviews tend to examine carbon management, sustainability education, or institutional transformation in isolation, lacking an integrated perspective that connects carbon literacy education with changes in student behavior. This fragmentation underscores the need for a comprehensive synthesis that explicitly links educational approaches, conceptual frameworks and behavioral outcomes within higher education contexts.

In response to these gaps, the present study systematically reviews the literature on carbon literacy and CO_2 emission education in higher education and their influence on student behavioral change. This review synthesizes empirical studies investigating how universities integrate carbon literacy into curricula, extracurricular initiatives, and institutional sustainability strategies, with particular attention to pedagogical approaches that translate climate knowledge into actionable competencies. The scope of this review focuses specifically on higher education contexts, emphasizing university-level educational interventions aimed at improving students' understanding of carbon emissions and encouraging low-carbon behaviors. By critically examining the conceptual frameworks, educational models, and behavioral outcomes reported in the literature, this review seeks to clarify the mechanisms through which carbon literacy education contributes to behavioral transformation among university students in the GCC. Furthermore, this study aims to identify recurring methodological limitations and emerging research trends, thereby providing a structured synthesis that informs future educational practices and research directions. This review advances knowledge on climate education in higher education by highlighting effective strategies for bridging the gap between environmental awareness and meaningful behavioral change, ultimately supporting the role of universities in fostering a generation capable of contributing to global climate mitigation efforts.

2. Methodology

This study employed a systematic literature review (SLR) approach to synthesize existing research on carbon literacy and CO_2 emission education in higher education and their influence on student behavioral changes. The review was conducted following widely recognized systematic review principles that emphasized transparency, reproducibility, and structured evidence synthesis. A systematic approach was chosen because research related to climate change education, carbon literacy, and behavioral transformation in higher education has expanded rapidly in recent years, yet the findings

remain fragmented across different disciplines, including environmental education, sustainability science, and higher education research. By systematically identifying, screening, and synthesizing relevant studies, this review aims to provide a comprehensive understanding of how carbon literacy education is conceptualized, implemented, and evaluated in university contexts. This review followed the PRISMA 2020 guidelines (Page et al., 2021) for systematic literature reviews (**Figure 1**).

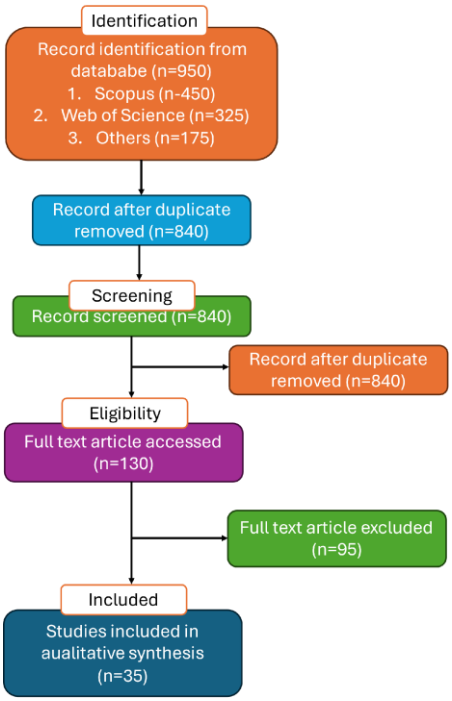

Figure 2. Systematic review flowchart process

The literature search was conducted using three major academic databases that index peer-reviewed literature across environmental science and education disciplines: Scopus, Web of Science, and ERIC. These databases were selected because they provide extensive coverage of high-quality international journals relevant to sustainability education, climate change, and higher education research. The search strategy employed combinations of keywords and Boolean operators to capture relevant studies addressing carbon literacy, CO_2 awareness, climate change education, and behavioral outcomes among university students. The search query included terms such as "carbon literacy," "CO_2 emission education," "climate change education," "carbon footprint," "higher education," "university students," and "behavioral change." To ensure the relevance and contemporary nature of the literature, the publication range was limited to studies published between 2015 and 2026. This timeframe was selected to capture research reflecting recent developments in climate education frameworks and sustainability initiatives within higher education institutions. Only peer-reviewed journal articles written in English were considered to maintain the academic quality and consistency.

Following the database search, the retrieved records were subjected to a multistage screening process to determine their eligibility for inclusion in the review. The screening procedure involved three sequential steps: removal of duplicate records, title and abstract screening, and full-text assessment of the remaining articles. Duplicate records identified in the databases were removed prior to further evaluation. In the title and abstract screening stage, studies were assessed to determine whether they addressed climate change education, carbon literacy, or CO_2 emission awareness within higher education contexts. Studies that focused exclusively on primary or secondary education, technological carbon accounting models without educational components, or general sustainability policies unrelated to student learning were excluded from the review. During the full-text screening stage, additional eligibility criteria were applied to ensure that the selected studies examined educational interventions, curricular

initiatives, or institutional programs related to carbon emission awareness and their potential influence on student knowledge, attitudes, or behaviors. This structured screening process ensured that the final dataset included only studies directly relevant to the review objectives.

After the final set of articles was determined, a structured data extraction process was conducted to facilitate the systematic synthesis of the literature. Key information extracted from each study included publication details, geographic context, research design, educational intervention type, theoretical frameworks, and reported outcomes related to carbon awareness and behavioral change. The extracted data were subsequently analyzed using a thematic synthesis approach to identify recurring patterns in the implementation and evaluation of carbon literacy education in higher education settings. Particular attention was given to pedagogical approaches, interdisciplinary educational models, and experiential learning strategies that aim to translate climate knowledge into practical and behavioral outcomes. Through this analytical process, the review integrates findings from diverse empirical studies to generate a coherent overview of current research trends, methodological approaches, and evidence regarding the effectiveness of CO_2 emission education in shaping student behavior within university environments.

3. Conceptualizing Carbon Literacy in Higher Education

Carbon literacy in higher education has been increasingly recognized as a central conceptual domain within sustainability education, aiming to equip students with the knowledge, skills, and values necessary to understand and mitigate carbon emissions (Molthan-Hill et al., 2019). As universities seek to respond to the growing urgency of climate change, carbon literacy has evolved from a narrow focus on climate awareness to a broader competency that integrates scientific understanding, behavioral engagement, and practical decision-making related to carbon emissions. Conceptually, carbon literacy refers to the capacity of individuals to understand the sources, consequences, and mitigation strategies of carbon emissions and translate this understanding into informed actions in personal and professional contexts. Within university environments, this concept is particularly important because students represent future professionals and decision-makers who will shape sustainability practices across various sectors. Consequently, numerous conceptual frameworks have been developed to explain how carbon literacy can be cultivated in higher education contexts. These frameworks draw on interdisciplinary perspectives, including systems thinking, behavioral science, constructivist pedagogy, and transformative learning. Together, these theoretical perspectives provide a foundation for understanding how students develop carbon awareness and how educational interventions can translate environmental knowledge into practical sustainable behaviors.

One of the most influential conceptual perspectives underpinning carbon literacy education is system thinking. Systems thinking emphasizes the interconnected nature of environmental, social, and economic systems and encourages learners to analyze sustainability challenges from a holistic perspective. In the context of climate change education, systems thinking enables students to understand the complex relationships among carbon emissions, ecological processes, and human activities. By examining feedback loops, causal relationships, and dynamic interactions within socio-ecological systems, students gain deeper insights into the mechanisms driving climate change and the potential impacts of mitigation strategies in the real world. Therefore, integrating systems thinking into sustainability education strengthens students' ability to conceptualize carbon cycling processes and understand the broader implications of human activities within environmental systems (Peretz, 2025). Earlier work on learning progressions in carbon cycling similarly highlights the importance of enabling students to connect ecological processes with societal activities, emphasizing conceptual modeling and socio-scientific reasoning as key elements in climate education (Mohan et al., 2009). In addition to conceptual understanding, analytical frameworks such as Life Cycle Assessment (LCA) have been widely used to operationalize carbon literacy through practical carbon footprint analysis. LCA frameworks allow students to evaluate the environmental impacts of products, services, and lifestyle choices by examining emissions across the production, consumption, and disposal stages. When combined with emerging

analytical approaches such as machine learning, these frameworks enable researchers and educators to identify behavioral emission patterns and better understand the determinants of individual carbon footprint. Empirical analyses of college student emissions, for instance, demonstrate that carbon awareness significantly influences emission-related behaviors, reinforcing the importance of integrating analytical tools with sustainability education (Cen et al., 2025). [insert citation] [insert citation] The relationship between carbon literacy education and student behavioral change can be conceptualized as a multidimensional framework integrating pedagogical approaches, psychological engagement, and institutional support (**Figure 2**).

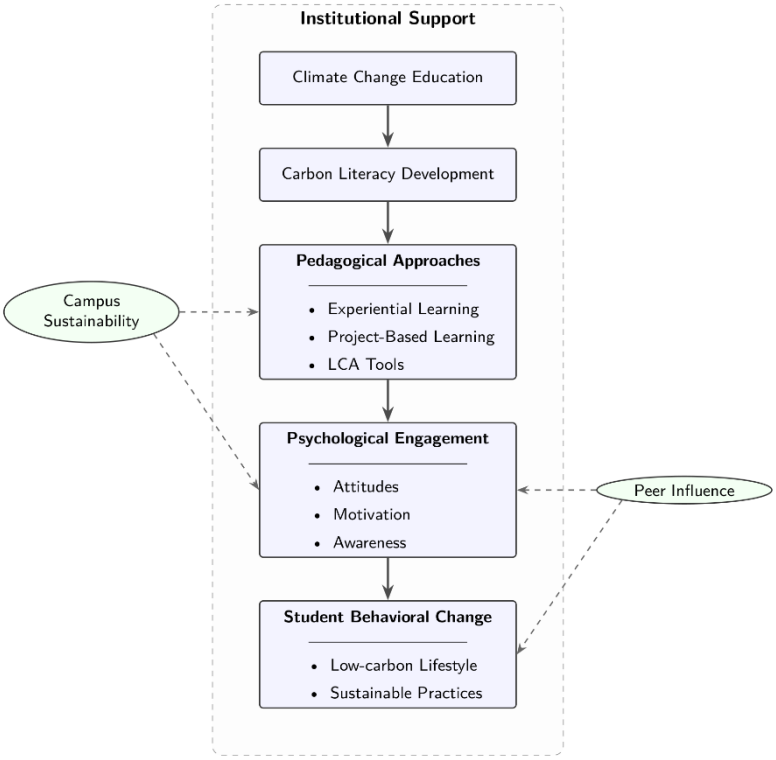

Figure 2. Conceptual framework illustrating the relationship between carbon literacy education, pedagogical approaches, and student behavioral change in higher-education institutions.

Beyond analytical frameworks, pedagogical approaches play a critical role in shaping the conceptualization of carbon literacy in higher education. Constructivist learning theories suggest that students develop meaningful understanding through active engagement with real-world problems, rather than passive knowledge acquisition. Within sustainability education, project-based learning and problem-oriented pedagogies have been widely used to strengthen students' understanding of carbon emissions and climate-mitigation strategies. Educational initiatives that involve students in analyzing the life cycle impacts of consumer products illustrate how experiential learning activities can integrate cognitive understanding with ethical reflection and emotional engagement (R. Zhang et al., 2025). Similarly, interdisciplinary studio-based learning environments allow students to explore sustainability challenges through scenario-based problem-solving, collaborative design exercises, and role-playing simulations that replicate real-world decision-making contexts (Moosavi and Bush, 2024). Through these experiential learning models, carbon literacy is embedded within professional and societal contexts, enabling students to develop practical competencies relevant to sustainability-oriented careers. Behavioral and psychological perspectives complement these pedagogical approaches by examining the motivational mechanisms influencing environmental decision-making. For instance, paradoxical thinking frameworks highlight the tension between competing motivations, such as comfort-oriented behaviors and normative environmental responsibilities. Research applying this framework to university

students shows that climate concern and social support for low-carbon norms significantly influence students' intentions to adopt sustainable behavior (Qian et al., 2026). In addition, carbon management frameworks encourage individuals to evaluate their personal emissions and identify opportunities for behavioral change. Studies analyzing personal carbon emissions within higher education institutions have demonstrated how lifestyle patterns, demographic factors, and consumption habits shape individual carbon footprints, reinforcing the need for educational strategies that encourage critical reflection on everyday environmental impacts (Bekaroo et al., 2019).

Curriculum design frameworks also provide important conceptual tools for integrating carbon literacy into higher education programs. One notable approach is the S3 model—"Simple, Serious, and Solvable"—which frames climate education around accessible scientific explanations, recognition of the seriousness of climate challenges, and identification of actionable mitigation strategies (Diaz-Clark et al., 2025). This model integrates scientific understanding with practical problem-solving activities, encouraging students to engage with climate issues through knowledge acquisition and behavioral action. Similarly, competency-based frameworks, such as the GreenComp framework, provide structured guidance for embedding sustainability competencies within university curricula. The GreenComp framework outlines 12 sustainability competencies that support curriculum development, assessment strategies, and institutional sustainability initiatives across disciplines (Mertens et al., 2024). Complementing these curricular frameworks, transformative learning theory emphasizes critical reflection and perspective transformation as key mechanisms for cultivating environmental responsibility. Transformative education encourages students to reconsider their assumptions about human–environment relationships and develop deeper ecological awareness through participatory and reflective learning experiences (Moore, 2005). Culturally informed pedagogical approaches further extend this perspective by integrating local cultural knowledge into sustainability education. For example, Ethno-Education for Sustainable Development (Ethno-ESD) frameworks contextualize environmental learning within cultural traditions and regional environmental practices, strengthening students' attitudes toward environmental stewardship and sustainability (Ariyatun et al., 2025). Critical literacy perspectives similarly emphasize the integration of scientific knowledge with sociopolitical awareness and ethical responsibility. Critical chemical literacy frameworks, for example, encourage students to analyze climate-related chemical processes while developing eco-reflexive agency and societal engagement in climate decision-making (Sjöström et al., 2024). Together with social practice perspectives that highlight the influence of everyday interactions and informal learning environments on climate knowledge development (Satchwell, 2013), these conceptual models collectively illustrate that carbon literacy emerges through the interaction of cognitive understanding, behavioral engagement, cultural context, and institutional learning environments. A summary of the Key Frameworks and Models with their focus and features is shown in **Table 1**.

Table 1. Summary of key frameworks and models

Framework/Model	Focus	Key Features
Systems Thinking	Socio-ecological systems	Feedback loops, conceptual modeling, and interdisciplinary reasoning (Mohan et al., 2009; Peretz, 2025).
Life Cycle Assessment (LCA)	Carbon footprint analysis	Integration of LCA and machine learning to analyze behavioral emission patterns (Cen et al., 2025).
S3 Model	Climate literacy	Hands-on activities, ethical discussions, and mitigation strategies that emphasize actionable solutions (Diaz-Clark et al., 2025).
Paradoxical Thinking	Behavioral psychology	Balancing hedonic and normative motivations influences low-carbon behaviors (Qian et al., 2026).

Framework/Model	Focus	Key Features
GreenComp Framework	Curriculum integration	Twelve sustainability competencies guide curriculum development and evaluation (Mertens et al., 2024).
Transformative Learning	Ecological literacy	Perspective transformation through collaborative and reflective learning (Moore 2005).
Critical Chemical Literacy	Climate empowerment	Integration of scientific knowledge with eco-reflexive agency and societal responsibility (Sjöström et al., 2024).

In summary, the conceptualization of carbon literacy in higher education reflects the convergence of multiple interdisciplinary frameworks that collectively explain how students develop environmental awareness and translate this knowledge into sustainable behavior. Systems thinking provides an analytical foundation for understanding complex environmental processes and socio-ecological interactions (Mohan et al., 2009; Peretz, 2025), whereas behavioral and psychological frameworks, such as paradoxical thinking, explain the motivational dynamics that influence environmental decision-making and low-carbon behavior (Qian et al., 2026). Pedagogical models, including life cycle assessment and competency-based approaches such as the GreenComp framework, translate these theoretical perspectives into practical educational strategies that foster sustainability competencies and support evidence-based decision making (Cen et al., 2025; Mertens et al., 2024). In addition, applied climate literacy models, such as the S3 framework, emphasize actionable learning through hands-on activities and solution-oriented thinking (Diaz-Clark et al., 2025). Transformative learning and critical literacy approaches further highlight the importance of ethical reflection, societal awareness, and eco-reflexive agency in shaping students' environmental perspectives and empowering climate action (Moore 2005; Sjöström et al. 2024). Together, these conceptual models provide a comprehensive theoretical foundation for designing educational programs that cultivate carbon literacy and prepare university students to actively engage in climate mitigation and sustainable development efforts.

4. Pedagogical Approaches to CO_2 Emission Education

Pedagogical approaches for teaching CO_2 emission reduction and carbon footprint awareness in higher education have evolved significantly in response to the increasing urgency of climate change and sustainability challenges (Ferguson 2019). Universities have adopted a wide range of teaching strategies designed to integrate scientific knowledge with practical engagement and behavioral transformation. Rather than relying solely on theoretical instruction, contemporary sustainability education emphasizes experiential, analytical, and interdisciplinary learning models that enable students to understand the environmental consequences of human activities and explore actionable solutions (Russell et al., 2016). In this context, CO_2 emission education is conceptualized as a multidimensional learning process that combines environmental science, behavioral understanding, and decision-making competencies. By integrating analytical tools, participatory learning, and institutional initiatives, universities aim to equip students with the technical knowledge and practical skills required to reduce carbon emissions in personal, professional, and societal contexts.

One of the most widely implemented pedagogical approaches involves integrating Life Cycle Assessment (LCA) and carbon quantification tools into university curricula. These analytical frameworks enable students to evaluate the environmental impacts associated with products, processes, or lifestyle activities by calculating the greenhouse gas emissions throughout the entire life cycle of goods and services. By incorporating carbon accounting exercises into their coursework, students develop systems thinking skills and gain a deeper understanding of how consumption patterns contribute to environmental degradation. Project-based learning activities that involve calculating the life cycle emissions of consumer products, such as clothing items, demonstrate how hands-on carbon footprint analysis can engage students cognitively, emotionally, and ethically in sustainability learning (R. Zhang

et al., 2025). Similarly, sustainability-oriented laboratory activities in engineering education allow students to analyze energy use, resource consumption, and emission generation in industrial processes, thereby strengthening their competencies in environmental assessment and mitigation (Sivanandam et al., 2024). Through these analytical approaches, carbon literacy education moves beyond abstract climate concepts and encourages students to apply quantitative methods to evaluate environmental impacts and design emission reduction solutions.

Digital and online learning models also represent an important pedagogical approach for advancing CO_2 emissions education while simultaneously reducing the environmental footprint of educational delivery. The adoption of online and distance learning platforms in higher education has expanded rapidly in recent years, offering opportunities to integrate sustainability principles into teaching. Beyond providing flexible access to educational resources, digital learning environments can significantly reduce the carbon emissions associated with transportation, campus energy consumption, and infrastructure maintenance. Comparative analyses of teaching models indicate that the carbon footprint associated with higher education delivery can be substantially reduced when online learning replaces traditional face-to-face instruction. In some cases, carbon emissions related to teaching activities have been reported to decrease by as much as 83% through the use of remote learning systems (Caird et al., 2015). In addition to reducing emissions associated with educational operations, digital learning platforms can enhance sustainability education by incorporating interactive tools, data visualization, and collaborative learning environments that support climate awareness and environmental analyses (Caird et al., 2015). By integrating information and communication technologies into sustainability education, universities can promote both environmental literacy and institutional decarbonization.

Participatory and service-learning approaches provide effective pedagogical strategies for teaching CO_2 emission reduction. These approaches emphasize active collaboration among students, educators, and community stakeholders in addressing environmental challenges through applied learning experiences. Sustainability-focused service-learning projects often involve students conducting environmental assessments, participating in climate action initiatives, and developing community-based sustainability programs. Such initiatives allow students to apply theoretical knowledge in real-world contexts, while fostering civic responsibility and environmental engagement. Empirical studies indicate that sustainability-related service-learning activities can enhance students' understanding of climate issues while promoting multidisciplinary collaboration and social awareness (Yi et al., 2025). However, research also emphasizes the importance of inclusive participation in these initiatives to ensure that community engagement processes remain meaningful and avoid perceptions of superficial involvement or tokenism (Guerra et al., 2025). When effectively implemented, participatory learning models can strengthen students' commitment to climate action by linking academic knowledge with tangible societal challenges such as climate change.

Interdisciplinary educational frameworks further strengthen CO_2 emission education by integrating knowledge from diverse academic and societal perspectives. Climate change is inherently complex and interconnected with multiple systems, including economic development, governance, and technological innovation. Consequently, educational approaches that combine insights from environmental science, policy studies, engineering, and social sciences are essential for developing comprehensive climate competencies among students. Pedagogical frameworks, such as the "Simple, Serious, Solvable" (S3) model, illustrate how climate education can be structured to present climate science in accessible terms, emphasize the urgency of environmental challenges, and highlight actionable mitigation strategies (Diaz-Clark et al., 2025). Similarly, transdisciplinary educational models encourage collaboration between academic disciplines and external stakeholders, allowing students to address real-world sustainability challenges through applied research and policy analysis (Kim, 2024). These interdisciplinary approaches foster critical thinking and enable students to understand the societal implications of climate change while exploring innovative solutions for emissions reduction.

Institutional sustainability frameworks also play a significant role in shaping pedagogical strategies for CO_2 emissions education within universities. Many higher education institutions have adopted sustainability initiatives aimed at achieving carbon neutrality and reducing campus emissions, creating opportunities to integrate operational sustainability practices into educational activities. Campus carbon audits, environmental management systems, and sustainability reporting initiatives often serve as practical learning platforms where students can directly engage in emission monitoring and mitigation strategies. Research on carbon-neutral university initiatives demonstrates how institutional sustainability strategies can enhance student learning by connecting campus operations to teaching and research activities (Udas et al., 2018). Similarly, large-scale institutional programs, such as the Sustainable Universities Initiative, combine emission assessment, carbon mitigation planning, and sustainability education to promote climate awareness within university communities (Magoo et al., 2024). In addition to institutional initiatives, technological innovations have further expanded the pedagogical potential of sustainability education. Digital transformation within universities enables the development of interactive learning tools, environmental monitoring systems, and data-driven platforms that allow students to analyze carbon emissions in real-time. Studies examining digital administrative systems have also indicated that replacing paper-based processes with digital alternatives can reduce material consumption and associated carbon emissions, thereby contributing to institutional sustainability goals (Herrera-Granda et al., 2024).

Specialized courses and international collaborative programs represent another important dimension of pedagogical innovation in CO_2 emissions education. Courses focusing on low-carbon technologies, environmental policy management, and sustainable development provide students with the technical knowledge and analytical skills necessary to address climate mitigation challenges. Educational initiatives addressing low-carbon technology and environmental governance emphasize the importance of interdisciplinary competencies in preparing students for sustainability-oriented professional roles (Yu et al., 2013). International collaborative programs, such as Erasmus+ sustainability courses, enable cross-cultural learning and knowledge exchange related to environmental management and sustainable construction practices (Selman and Verdonck, 2025). These programs expose students to diverse environmental perspectives and encourage global collaboration to address climate challenges. By integrating analytical tools, participatory learning, institutional sustainability initiatives, and global collaboration, universities can create educational environments that foster knowledge acquisition and behavioral transformation. A summary of the Key Pedagogical Approaches and their impact is shown in **Table 2**.

Table 2. Summary of key pedagogical approaches

Approach	Key Features	Impact
LCA and Carbon Quantification	Practical tools for calculating emissions and evaluating life cycle environmental impacts (Zhang et al., 2025; Sivanandam et al., 2024).	It improves systems thinking and students' ability to assess sustainability impacts.
Online/Distance Learning Models	ICT-based teaching methods that reduce travel and campus energy consumption (Caird et al., 2015).	Significant reduction in educational carbon emissions while supporting learning accessibility.
Participatory Methods	Community-based climate action and service-learning projects (Yi et al., 2025; Guerra et al., 2025).	It encourages stakeholder collaboration and applies sustainability learning.
Interdisciplinary Education	Active learning frameworks integrate climate science, ethics, and policy	Strengthens climate literacy and problem-solving competency.

Approach	Key Features	Impact
	discussions (Diaz-Clark et al., 2025; Kim, 2024).	
Institutional Frameworks	Campus carbon neutrality strategies have been integrated into teaching and research (Udas et al., 2018; Magoo et al., 2024).	Align institutional operations with sustainability education.
Technology-Driven Approaches	Digital systems reduce resource use and support environmental analyses (Herrera-Granda et al., 2024).	It enhances institutional efficiency and climate awareness.
Specialized Courses	Courses on low-carbon technologies and international sustainability collaboration (Yu et al., 2013; Selman & Verdonck, 2025).	It prepares students for sustainability-oriented professional roles.

Overall, pedagogical approaches to CO_2 emission education in higher education have increasingly emphasized experiential learning, interdisciplinary collaboration, digital innovation, and institutional transformation. By combining analytical tools, participatory engagement, and sustainability-oriented curricula, universities can create educational environments that enhance students' understanding of climate change and empower them to actively contribute to carbon emission reduction and broader sustainability goals.

5. Impact on Student Behavioral Change

Carbon literacy and CO_2 emission education have been increasingly recognized as influential drivers of pro-environmental behavioral change among university students (Y. Zhang et al., 2025). Within higher education institutions, environmental education initiatives are designed to improve students' understanding of climate science and to shape the attitudes, motivations, and actions necessary for reducing carbon emissions (Tang, 2022). The relationship between educational interventions and behavioral outcomes is inherently complex, involving the interaction of cognitive knowledge, psychological engagement, social norms, and institutional contexts. When effectively implemented, carbon literacy education can foster students' awareness of environmental challenges and encourage them to adopt sustainable lifestyle practices that contribute to climate mitigation. Consequently, higher education institutions play a critical role in shaping environmentally responsible citizens capable of integrating sustainability considerations into both personal decision-making and professional practices.

One of the most consistent impacts of carbon literacy education is the enhancement of students' climate knowledge and beliefs regarding the feasibility of climate action. Educational programs that focus on climate science and mitigation strategies have been shown to significantly improve students' understanding of environmental systems and strengthen their confidence in responding to climate change. For instance, the "Bending the Curve" climate solutions course demonstrated that students who participated in the program developed greater confidence in the scientific foundations of climate change, while also expressing stronger belief in society's ability to address environmental challenges through coordinated action (Gupta et al., 2025). Similarly, carbon literacy initiatives emphasize actionable knowledge that connects scientific understanding with practical mitigation. Programs such as the Carbon Literacy Project provide participants with tools and competencies that allow them to interpret carbon-related information and apply emission reduction strategies in everyday decision-making contexts (Matharu Srkoc et al., 2022; Molthan-Hill et al., 2025). These educational approaches highlight the importance of bridging scientific knowledge with practical climate solutions, thereby strengthening students' sense of agency and responsibility in the face of environmental challenges.

Beyond knowledge development, carbon literacy education influences students' environmental attitudes and behavioral intentions. Environmental attitudes represent individuals' evaluations and

values regarding environmental protection and often function as psychological precursors to behavioral decisions. Studies examining sustainability education among university students have demonstrated that exposure to environmental curricula can significantly enhance students' environmental awareness while fostering more positive attitudes toward sustainable lifestyles (Zsóka et al., 2013). Similarly, research investigating university students' perceptions of sustainability education shows that educational experiences can strengthen students' understanding of environmental problems and encourage them to adopt pro-environmental perspectives (Boca and Saraçli, 2019). More recent studies suggest that environmental education indirectly influences low-carbon behavior through mediating factors such as environmental attitudes and perceived environmental value (Yang et al., 2025). Within this framework, educational experiences strengthen environmental attitudes, which subsequently influence behavioral intentions and decision-making processes related to sustainability practices. For example, sustainability education programs have been shown to increase students' willingness to engage in activities such as waste separation, energy conservation, and environmentally responsible consumption (Franco et al., 2022; Thanh Binh et al., 2025).

Despite these positive impacts, the relationship between climate education and actual behavioral change remains complex and inconsistent. Several studies have highlighted the persistence of an "awareness–action gap," wherein students demonstrate strong environmental knowledge but fail to consistently translate this knowledge into sustainable behaviors. Research exploring the relationship between education and environmental behavior suggests that although educational interventions can positively influence attitudes and intentions, their direct effect on long-term behavioral change may be limited without supportive contextual factors (Powdthavee 2021). Similarly, analyses of student lifestyle emissions indicate that individuals often express support for climate mitigation strategies but encounter practical barriers when attempting to implement these behaviors in everyday contexts (Zhu et al., 2026). These findings underscore the importance of integrating behavioral reinforcement mechanisms, institutional support systems, and experiential learning opportunities into sustainability education programmes to strengthen the translation of knowledge into action.

Psychological and emotional factors further mediate the effectiveness of carbon literacy education in promoting sustainable behaviors. Educational interventions that incorporate emotional engagement and psychological training can strengthen students' abilities to sustain environmental action over time. For example, experimental studies examining Mental Mode Management (MMM) training demonstrate that psychological interventions aimed at improving emotional regulation and mindfulness can enhance pro-environmental behavior while reducing climate-related anxiety among participants (Colombo et al., 2025). Emotional rewards associated with environmentally responsible actions can reinforce sustainable behavior. Research examining behavioral patterns among university students suggests that feelings of personal satisfaction and accomplishment derived from sustainability actions can encourage continued engagement in pro-environmental practices (Fang 2021). These findings indicate that educational programs that address emotional engagement and psychological well-being may play a crucial role in sustaining long-term environmental commitment among student populations.

Another important factor influencing behavioral change is the social and institutional context in which sustainability education occurs. Collaborative learning environments and peer interactions can significantly shape students' environmental behavior by reinforcing social norms related to sustainability. Educational interventions that incorporate group discussions, collaborative problem-solving, and shared learning experiences have been shown to increase students' motivation to participate in climate action initiatives (Moore et al., 2026). Embedding sustainability education across multiple academic disciplines can strengthen the relevance of environmental issues within different professional contexts, thereby encouraging students to integrate sustainability principles into their future careers (Anderson, 2024). Innovative educational approaches, such as experiential learning and game-based climate education, further demonstrate the potential for strengthening long-term behavioral engagement by creating interactive and emotionally meaningful learning experiences (Demir Yıldız, 2025). Moreover, the

influence of climate education can extend beyond individual behavioral changes, encouraging students to participate in broader environmental initiatives, policy advocacy, and community-based sustainability projects (Zhang et al., 2022). An overview of the Key Findings on Climate Education Effectiveness and Challenges is shown in **Table 3**.

Table 3. Summary of key impact on behavior change

Key Impact Areas	Findings
Knowledge Enhancement	Climate education improves understanding of climate science and strengthens beliefs in actionable climate solutions (Gupta et al., 2025; Matharu Srkoc et al., 2022).
Behavioral Change	Students adopt sustainable behaviors, such as waste reduction and low-emission consumption practices (Gupta et al., 2025; Moore et al., 2026).
Emotional Resilience	Psychological interventions enhance emotional engagement and support sustained pro-environmental actions (Colombo et al., 2025).
Challenges	Awareness–action gap and difficulties in applying theoretical knowledge to real-life contexts (Hijazi et al., 2025; Powdthavee, 2021).
Recommendations	Experiential learning, interdisciplinary curricula, and social learning environments enhance the effectiveness of climate education (Anderson, 2024; Moore et al., 2026).

Overall, carbon literacy and climate change education have significant potential to influence students' environmental attitudes, intentions, and behaviors in higher education contexts. Educational initiatives that combine scientific knowledge with practical tools, emotional engagement, and collaborative learning environments are particularly effective in promoting sustainable behavioral change. However, the translation of climate awareness into consistent, long-term action is influenced by psychological, social, and institutional factors. Addressing these factors through integrated educational strategies can enhance the effectiveness of carbon literacy programs and strengthen the role of universities in fostering environmentally responsible behavior among future generations.

6. Discussion

The findings of this review demonstrate that carbon literacy education in higher education operates through a dynamic interplay between cognitive, analytical, and socio-emotional learning processes rather than through isolated instructional strategies. While the previous sections identified a range of pedagogical approaches, a critical synthesis revealed that these approaches differ significantly in their mechanisms for influencing student behavior. Analytical approaches, such as Life Cycle Assessment (LCA) and carbon footprint quantification tools, primarily enhance students' cognitive awareness by providing measurable and data-driven insights into emissions. In contrast, participatory and experiential approaches, including service learning and collaborative sustainability projects, engage students at the social and emotional levels, fostering a sense of responsibility, agency, and collective action. This distinction suggests that no single pedagogical approach is sufficient; instead, effective carbon literacy education emerges from integrating analytical rigor with socially embedded learning experiences.

A key insight emerging from this synthesis is the differential effectiveness of these approaches in addressing the awareness–action gap. Analytical tools such as LCA are highly effective in improving knowledge accuracy and enabling students to understand the environmental consequences of their behavior in quantitative terms. However, evidence from the reviewed literature indicates that such approaches alone often fail to produce sustained behavioral change, as they primarily target cognitive understanding without sufficiently addressing motivational and contextual factors. Conversely, participatory and experiential learning approaches appear more effective in translating awareness into action as they embed sustainability practices within real-world social contexts and reinforce behavioral norms through peer interaction and community engagement. However, these approaches may lack the

analytical depth required for informed decision-making if not complemented by data-driven tools. Therefore, the most effective strategy for bridging the awareness–action gap lies in hybrid pedagogical models that combine analytical tools with participatory and experiential learning, enabling both understanding and action-oriented engagement to be achieved.

These findings have important implications for the theoretical development of environmental and sustainability education. The results strongly support and extend Transformative Learning Theory, which emphasizes critical reflection, experiential engagement, and perspective transformation as key drivers of behavioral change. The evidence suggests that carbon literacy education aligns with transformative learning processes when it moves beyond knowledge transmission to challenge students' assumptions, values, and practices. In particular, participatory and experiential approaches facilitate "perspective transformation" by situating students within real-world sustainability challenges, thereby encouraging critical reflection on personal and societal roles in climate change. Simultaneously, the integration of analytical tools, such as LCA, extends transformative learning by incorporating evidence-based reasoning into reflective processes, suggesting a hybrid model in which cognitive and affective dimensions are mutually reinforcing rather than separate.

Furthermore, the findings contribute to refining the behavioral frameworks commonly used in sustainability education, such as the knowledge–attitude–behavior (KAB) model. The persistence of the awareness–action gap observed in the literature challenges the linear assumptions of this model, indicating that knowledge acquisition does not automatically translate into behavioral change. Instead, the results support more complex frameworks that incorporate mediating variables, such as emotional engagement, social norms, and institutional contexts. In this regard, carbon literacy education can be conceptualized as a multidimensional process in which behavioral outcomes are shaped by the interaction of cognitive understanding, psychological motivation, and social reinforcement. This perspective extends existing theoretical models by emphasizing the importance of integrating affective and contextual factors into the educational design.

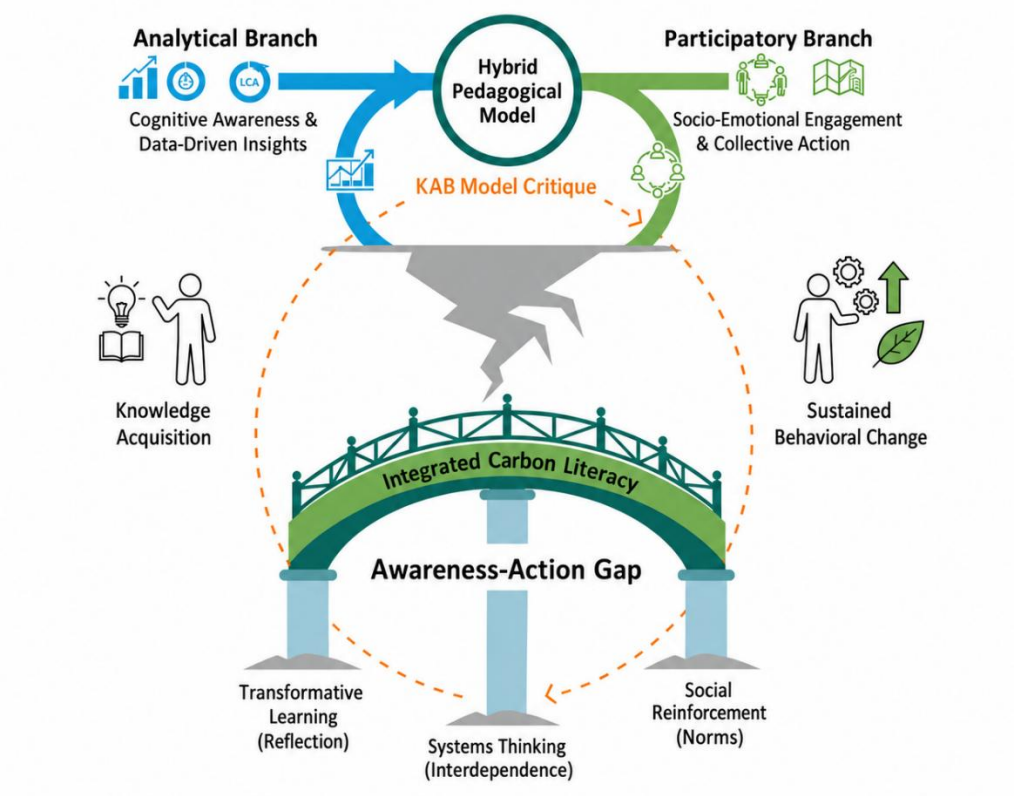

Figure 3. Institutional context: Campus operations and Sustainability Governance

Another important theoretical implication relates to the systems thinking frameworks in sustainability education. The integration of interdisciplinary and experiential learning approaches reflects a shift toward viewing climate change as a complex socio-ecological system, rather than a purely scientific problem. The findings suggest that carbon literacy education is most effective when students are encouraged to understand feedback loops, interdependencies, and the systemic impact of their actions. This aligns with systems thinking theory, while also extending it by demonstrating how systems-based understanding can be operationalized through practical learning experiences and behavioral interventions. In this sense, carbon literacy serves as a bridge between abstract systems thinking and concrete behavioral practice.

Institutional context also emerges as a critical moderating factor influencing both pedagogical effectiveness and theoretical interpretation. Universities that align curriculum, campus operations, and sustainability governance create environments that reinforce learning through consistent signals and practices (**Figure 3**). This finding supports sociocultural learning theories, which emphasize that knowledge is constructed through interaction with social and institutional environments. This also suggests that transformative learning in sustainability cannot occur solely at the individual level but must be supported by institutional structures that enable and normalize sustainable behavior. Conversely, inconsistencies between institutional discourse and practice may undermine both learning outcomes and theoretical assumptions regarding behavior change.

Overall, this discussion advances the understanding of carbon literacy education by positioning it as an integrative framework that combines analytical, experiential and socio-institutional dimensions. The synthesis highlights that effective behavioral change requires not only knowledge acquisition but also emotional engagement, social reinforcement, and supportive institutional contexts. By bridging pedagogical approaches and theoretical frameworks, this review contributes to a comprehensive understanding of how higher education can facilitate meaningful and sustained transitions toward low-carbon behaviors.

7. Implications for Higher Education Policy and Practice

The findings of this review highlight the strategic role of higher education institutions (HEIs) in advancing sustainability transitions by integrating carbon literacy and climate action education into institutional policies, curricula, and operational practices. Universities function not only as centers of knowledge production but also as agents of societal transformation, capable of shaping environmental awareness, sustainability competencies, and climate-related decision-making among students. Consequently, the implications of carbon literacy education extend beyond pedagogical innovation and require coordinated policy frameworks that integrate academic learning, institutional governance and operational sustainability practices. Embedding carbon literacy within higher education therefore demands a comprehensive institutional approach that aligns teaching, research, campus management, and community engagement with broader sustainability objectives to achieve carbon neutrality.

One of the most significant policy implications is the integration of carbon literacy into academic curricula. Climate change is a complex global challenge that intersects with multiple disciplinary domains, including engineering, economics, policy studies, and social sciences. Consequently, sustainability education should not be confined to specialized environmental courses but should be embedded across diverse academic programs. Integrating climate literacy into business education, for example, has demonstrated how interdisciplinary curricula aligned with Sustainable Development Goal 13 can promote sustainability leadership and strengthen students' understanding of climate-mitigation strategies (Elsayed et al., 2025). Similarly, educational frameworks for climate change education emphasize the importance of incorporating climate literacy across disciplines to ensure that students from diverse academic backgrounds acquire the competencies required to address environmental challenges (Molthan-Hill et al., 2022). Case studies examining climate literacy programs further indicate that embedding climate education within formal curricula enhances students' environmental awareness

and encourages participation in climate action initiatives (Hijazi et al., 2025). Such curricular integration recognizes climate change as a cross-cutting issue requiring interdisciplinary knowledge and collaborative problem-solving.

Beyond curricular innovation, whole-institution approaches represent a critical strategy for integrating carbon literacy into higher-education policy and practice. Whole-institution models emphasize embedding sustainability principles across all dimensions of university operations, including teaching, research, governance, and campus management, to achieve sustainability. Universities adopting such models often align their educational programs with global sustainability frameworks, such as the United Nations Sustainable Development Goals (SDGs), thereby strengthening their institutional commitment to sustainability. Research examining institutional strategies for Education for Sustainable Development indicates that integrating SDG-related learning outcomes across academic programs can significantly enhance student engagement and sustainability competency (Price et al., 2024). Furthermore, transdisciplinary educational initiatives that involve collaboration among academic departments enable universities to develop integrated curricula capable of addressing complex environmental challenges through interdisciplinary knowledge production (White et al. 2025). These institutional strategies highlight the importance of systemic integration over isolated sustainability initiatives.

Competency-based educational frameworks also have important implications for developing and evaluating carbon literacy initiatives within universities. Frameworks designed to measure climate action competencies provide valuable tools for assessing the effectiveness of sustainability education programs. For instance, the Climate Action Competence Scale (CACS) was developed to evaluate individuals' climate knowledge, efficacy beliefs, and commitment to climate action (Tseng et al., 2025). The use of such assessment tools allows universities to monitor the development of sustainability competencies among students and identify areas for improvement in educational programs. In addition to student learning outcomes, teacher education programs play a crucial role in supporting carbon literacy. Preparing educators to teach climate change and sustainability topics effectively ensures that climate education can be integrated across diverse academic disciplines and educational levels (Winter et al., 2022). Frameworks designed for pre-service teacher training further emphasize the need to equip educators with both the scientific knowledge and pedagogical skills required for delivering effective climate education (Reed Johnson et al., 2025).

Another important implication is the role of collaborative partnerships and transdisciplinary engagement in advancing sustainability education. Universities are increasingly collaborating with external stakeholders, including governments, schools, and industry partners, to support climate action initiatives and sustainability innovation. Educational alliances linking universities with school systems, for example, enable the expansion of climate literacy programs beyond higher education and promote knowledge exchange between educational institutions (Galdames and Saracostti 2025). Similarly, transdisciplinary research initiatives focusing on urban climate transitions demonstrate how universities can collaborate with policymakers and community stakeholders to develop practical solutions for environmental challenges (Rohracher and Kordas, 2024). Partnerships with industry also contribute to sustainability innovation by facilitating co-learning processes and supporting carbon management initiatives within broader socioeconomic systems (Earley et al., 2024).

Institutional governance frameworks also play a critical role in enabling the successful implementation of carbon literacy strategies in universities. Governance models that embed sustainability principles into institutional decision-making processes are essential for coordinating climate action across academic and operational spheres. Structured governance initiatives, such as the Sustainable Universities Initiative, illustrate how universities can systematically reduce carbon emissions through integrated assessment, planning, and implementation processes (Magoo et al., 2024). Similarly, system dynamics approaches have been developed to help institutions analyze complex sustainability transitions and identify barriers to green transformation within university systems (Franco et al., 2025).

Collaborative governance networks involving university leadership, academic departments, administrative units, and external stakeholders further facilitate the implementation of climate action initiatives by promoting coordinated decision making across institutional structures (Jimu and Rennkamp, 2023).

Operational decarbonization strategies also reinforce carbon literacy education by aligning campus practices with sustainable principles. Many universities have implemented decarbonization initiatives, including transitioning to renewable energy systems, improving energy efficiency in campus infrastructure, and promoting sustainable transportation policies. Studies examining university mitigation strategies emphasize the importance of addressing greenhouse gas emissions across multiple operational scopes, including those associated with commuting and business travel (Rinollo et al., 2025). The adoption of standardized carbon accounting frameworks, such as ISO 14064-1 further enables universities to systematically measure and manage their emissions while identifying opportunities for reduction (Tsai et al., 2025). Green Campus initiatives similarly demonstrate how visible sustainability programs, such as energy conservation campaigns, waste reduction initiatives, and biodiversity protection programs, can strengthen environmental awareness among students and staff while reinforcing institutional commitments to climate action (Gungor et al., 2025). These initiatives transform university campuses into living laboratories, where sustainability principles are integrated into everyday institutional practices.

Despite these promising developments, several challenges continue to hinder the effective implementation of carbon literacy and climate action education in higher education institutions. Financial limitations, fragmented governance structures, and inconsistent institutional commitment can restrict the scope of sustainability initiatives (Gungor et al., 2025; Jimu and Rennkamp, 2023). In addition, inconsistencies in carbon footprint measurement methodologies and sustainability reporting standards complicate efforts to evaluate institutional progress toward decarbonization goals (Da Silva et al., 2023). Addressing these challenges requires stronger institutional support mechanisms, enhanced stakeholder collaboration, and the development of standardized frameworks for sustainability education. Effective communication strategies that promote sustainability awareness across university communities can facilitate cultural shifts toward environmental responsibility (Mitra and Roy, 2025). Moreover, research on sustainable development literacy suggests that institutional environments, including curriculum design, campus culture, and student engagement initiatives, play a decisive role in shaping the effectiveness of sustainability education (Qi et al., 2023).

Overall, the policy and practical implications of carbon literacy education emphasize the need for integrated institutional strategies that combine curricular innovation, competency development, collaborative governance, and operational sustainability initiatives. Universities that adopt comprehensive whole-institution approaches are better positioned to align their educational programs with institutional climate goals while fostering environmental responsibility among students and staff. By embedding sustainability principles within academic curricula and institutional governance structures, higher education institutions can play a transformative role in advancing global climate mitigation efforts and preparing future generations to address the complex challenges of sustainable development.

8. Conclusion

This review synthesizes current research on carbon literacy and CO_2 emission education in higher education, highlighting their roles in fostering environmental awareness and promoting pro-environmental behavioral change among university students. The findings indicate that carbon literacy education contributes to improving students' climate knowledge, strengthening their environmental attitudes, and increasing their willingness to adopt sustainable behaviors. Pedagogical approaches, such as experiential learning, project-based learning, interdisciplinary curricula, and institutional sustainability initiatives, provide important mechanisms for translating climate knowledge into practical

action. These approaches enable students to understand the environmental implications of their daily activities while developing the competencies required to participate in climate mitigation efforts. Despite these positive outcomes, the literature consistently reveals challenges in bridging the gap between environmental awareness and sustainable behavioral change. Psychological, social, and institutional factors influence students' ability to consistently translate climate knowledge into low-carbon practices. Consequently, effective carbon literacy education requires integrated strategies that combine cognitive learning with experiential engagement, social reinforcement, and a supportive institutional environment. Therefore, higher education institutions play a transformative role in advancing sustainability transitions by embedding carbon literacy across curricula, institutional governance, and campus operations. Strengthening interdisciplinary collaboration, expanding experiential learning opportunities, and aligning institutional policies with climate education objectives are essential for preparing university graduates to actively contribute to global efforts toward low-carbon and sustainable societies.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) used ChatGPT to improve readability, correct grammatical errors, and assist in summarizing paragraphs into tables, and GPAI to support visual development. After using these tools/services, the author(s) carefully reviewed and edited the content as needed and took (s) full responsibility for the content of the published article.

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